Nonlinear seismic performance evaluation of existing infrastructures – State of the art

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ABSTRACT

An advanced performance-based seismic design and maintenance scheme for infrastructure is currently under development. This scheme aims to quantitatively assess the risk, safety, serviceability, and durability of both urban and national assets under expected loads and ambient actions in future. The framework is currently being employed for assessing the performance of existing infrastructure in terms of structural reliability and resilience, as well as for the design of new constructions. In certain regions, urban regeneration necessitates strengthening, repair, and replacement of whole or part of existing infrastructure. To address this challenge, structural behavioral simulation technology is considered a powerful tool within the realm of cyberspace. This technology can mirror real-world conditions, including natural environments and events such as earthquakes, over the service life of structures.

In the 1980s, extensive research and development efforts were undertaken worldwide to create nonlinear models of solid concrete with cracks, forming the foundation of nonlinear dynamic simulation. It's worth noting that significant emphasis was placed on experimental verification and validation (V&V) to establish the applicability of computational models. This deepened our understanding of structural concrete mechanics like consistently driven wheels of cars. During this period, there was a particular focus on addressing multi-directional cracks, which are crucial for seismic analysis involving complex reversed cyclic loads. Various approaches were explored, including fixed versus rotating crack models and orthogonal versus non-orthogonal crack interactions. Ultimately, the multi-directional non-orthogonal crack approach was selected in the 2000s due to its versatility and applicability in complex durability mechanics.

Since the 2010s, with the rapid advancement of IT capabilities, nonlinear 3D dynamic analyses have become capable of personalizing design and planning. Significant progress has been made in assessing the performance of structural concrete, with 3D ground motions leading to naturally occurring multi-directional crack-to-crack intersections. Additionally, traffic loads applied to bridges result in repeated rotations of principal stresses. Consequently, shear transfer, a source of non-orthogonal crack interaction, plays a critical role in ensuring the static, dynamic, and fatigue safety of structures. Furthermore, multi-directional cracking can lead to graveling, an extreme consequence for concrete composites. Presently, limit state analyses are crucial for evaluating the resilience performance, ranging from prevention of collapse to the normal use of infrastructure after earthquake disaster. Research into structural concrete now encompasses the post-peak stage up to the extreme states of collapse of structural members.

In a practical context, there is a growing need for nonlinear seismic performance evaluation of existing infrastructure. One critical aspect is the seismic performance assessment of structures constructed over half a century ago. This challenge is linked to the dynamic thermo-hygral state that causes volume changes in constituent materials. In the 2010s, long-term excessive displacement and deformation of long-span bridges were observed under typical loads and climatic conditions, with the cause traced to moisture kinetics in micro-pores of concrete. Aseismic resistance and dynamic behaviors under earthquake actions are also influenced over time. This underscores the importance of amalgamating knowledge from structural mechanics and material sciences to meet societal challenges. Another key concern is the interaction with soil foundations in the seismic design and maintenance of both underground and above-ground infrastructure. The shear localized band of ground, or fault, presents a critical issue for safety assessments and resilience of underground facilities such as tunnels and lifelines. While liquefaction of foundations may result in less damage to individual underground spaces, it can lead to massive damage to serviceability of the entire infra-systems. Notably, the mechanics of cracked concrete and soil with pore water share a common theory of multi-phases. Therefore, it is imperative to establish an integrated framework for infrastructure and foundation systems, treating them as unified mechanical and chemical systems, especially when addressing various urban challenges.

Koichi Maekawa earned D.Eng. in Civil Engineering from The University of Tokyo (UT), Japan, and served as a faculty in UT from 1985 to 2018, and Yokohama National University till 2023. Prof. Maekawa continuously has worked to develop thermo-mechanistic modeling of structural concrete for the past 30 years and computational platform to assess structural performance in practice. He was also involved in development of self-compacting concrete, and performance based seismic and durability design of concrete infrastructures as a Chair of Concrete Committee and a Vice President of Japan Society of Civil Engineers and Japan Concrete Institute. Now, Prof. Maekawa is a member of Science Council of Japan and Chairman of Ueda Memorial Foundation.